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ANALOG NETWORK REPRESENTATION OF INTERDIGITAL SURFACE WAVE TRANSDUCERS

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Army Electronics Command
Fort Monmouth, New Jersey

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Analog networks for surface waves are introduced and illustrated. Transmission lines represent regions of propagation, and piezoelectric transduction appears as ideal transformers at electrode edges producing delta-functions of traction. Advantages of using an analog-type description are discussed.

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CONTENTS

INTRODUCTION

Interdigital arrays are the most popular means of producing acoustic surface waves on piezoelectric crystals, because of the direct transduction that takes place. Considerable effort has therefore been devoted to achieve an adequate characterization of their behavior; this has largely taken the direction of finding equivalent electrical circuits that model the port relations of the structure. In the early and important letter by Krairojananan and Redwood,[1] the Mason bulk-wave circuit was first applied to the surface wave case. Moreover, the acoustic transmission line portion was depicted as a spatially-distributed coaxial line,[2] rather than in usual tee circuit form. This refinement lends a graphic quality to the network schematic and leads in a natural fashion to the concept of an analog network, to be described subsequently.

The electrode and gap regions were represented by a series of identical transmission lines arranged mechanically in cascade; lines for either region were invested with a piezoelectric driving source, and the other region considered piezoelectrically inert. Both of these alternative arrangements place the piezoelectric sources at the edges of the array of fingers; however, this is not emphasized in the circuit picture, as the piezo network is attached to the center of the coaxial sheath.

Other authors used a single transmission line (in lumped, tee form) to accomodate a periodic segment of gap-plus-electrode regions, with the piezoelectric sources located effectively at the centers of the electrodes,[3] or the gaps.[4] Judd, Morse and Smith[5] were apparently first to account for the discontinuities at the electrode edges, due to changes in mass-loading and electrical conditions; they used two acoustic lines per repeat-length having differing impedances and wavenumbers. The line lengths were equal to the corresponding geometrical lengths of electrode and gap, while both transmission lines were piezoelectrically excited by sources placed equivalently at the electrode edges. A similar treatment by Jones, Hartmann and Sturdivant[6] used two lines of differing impedance, but of identical wave number; the line representing the gap is inert, and the other is driven so that the electrode edges are the sites of the piezoelectric sources.

Although alluded to in Reference 1, Smith <u>et al</u>.[3] first discussed modifications of the electrical port input circuit arising from the nature of the transduction mechanism. A negative capacitance appears in the bulk-wave input circuit if the electric field produced by the wave motion lies along the direction of the driving field, and is absent if the fields are perpendicular.

Because neither the finger array nor the resulting surface wave produces a spatially unvarying field pattern, in general the fields will make an angle with respect to one another, and the angle will be a function of position in the sagittal plane. Hence, the composition of the electrical input network is not clear. Smith et al.[3] treated both limiting cases, which they referred to as 'in-line' (fields parallel) and 'crossed-field' (fields normal).

An intermediate form of the equivalent circuit, assuming no mechanical discontinuities but accounting for the composite type of excitation, was introduced by Milsom and Redwood.[7] In it, transmission lines of one kind only are used; they alternate between being piezoelectrically active and inert, with the inert lines centered at the middle of the electrodes and the active lines centered on the gap centers. The line ends do not coincide, however, with the electrode edges, but their lengths are so chosen that the excitation sources are offset from the edges by a factor depending on the metallization ratio (width-of-electrode to width-of-electrode-plus-gap). The negative capacitance and line wavenumber are likewise modified by this ratio.

In each of the equivalent circuits described above, the major thrust of the development has been to model the port relations of devices as closely as possible, consistent with reasonable simplicity. Adjustable parameters provide the latitude required to fit experimental data without necessarily attempting to make the network and physical pictures accord in any detailed fashion. Apart from the very great number of variations of these ad hoc circuits, and the possible confusion over their suitability in a given instance, they possess a number of drawbacks. Firstly, it is not straightforwardly apparent how these networks would be modified to take into account a new feature in the structure, such as grooves parallel to the digitations, variable electrode and gap widths, non-alternating electrode polarity patterns, or dummy electrodes, whether conducting or dielectric. Secondly, one lacks an obvious method of reducing an accurate but inordinately complex network to a simpler engineering approximation, as might be warranted by experimental accuracy and/or computational resources, in a systematic manner such that all circuit features of relevance are retained to the same order of approximation.

Global equivalent networks, of the types mentioned, that characterize devices only as regards the immittances seen at the ports are not constrained to any detailed geometric or topological resemblance of the physical aspects of the devices. Analog networks, which are locally equivalent circuits, are constrained by the requirement that their variables match those of the devices on a point-to-point basis insofar as possible; this allows the network structure to be put down almost by inspection once the one-dimensional acoustic guiding structure and network components are determined. Such networks have recently been introduced for bulk modes.[8] Their development follows from the suggestive form of the network schematic in Reference 2, and the use of microwave network formalism for acoustic problems.[9]

ANALOG NETWORK REPRESENTATION

Construction of surface wave analog circuits proceeds in similar fashion; microwave methodology introduces the concept of transmission-line modal representations for regions of propagation, lumped circuits for discontinuities and junctions, and the building-block approach. The existence of a one-dimensional wave solution implies a transmission-line representation. Regardless of the type of surface wave and the complexity of the resulting motion, so long as the supporting structure is translationally invariant in one direction, such a representation exists. Associated with the line carrying the mode are vector functions characteristic of the medium and geometry of the structure.[9] A line is required for each gap and electrode; its length is precisely equal to the geometrical length of the region, and its parameters depend on the wave solution in that region.

Discontinuities of two types occur at finger edges. Gap and electrode portions differ in mass-loading, elastic properties and conductivity; the two regions hence have different acoustic impedance, wavenumber and vector mode functions, and this produces a mechanical discontinuity. The second kind arises from the piezoelectric nature of the medium. For negligibly thin electrodes the surface electric field strength at the edges approaches a branch-point singularity; for non-zero electrode thickness the fields in the immediate vicinity of the gap edges are finite, but very large, in comparison with elsewhere in the gap. Since piezoelectric tractions are proportional to electric field strength, they are largest at the edges. The electric field gradient, which yields the force-density, is consequently represented to an excellent approximation by Dirac δ -function sources placed at the edges. This result is used in the delta-function method that regards the action of the complete transducer array as resulting from the algebraic sum of individual piezoelectric sources spaced along the array, each source constituting a Dirac delta-function.[10] Whereas this method is a purely mathematical approach to evaluating surface wave tranducers, its connection with the circuit picture was convincingly demonstrated by Mitchell and Reilly.[11]

At the electrode edges, then, circuits representing the two types of discontinuity are required. The mechanical network is realized by a combination of inductance and capacitance elements for reactive energy storage of cut-off modes, and transmission lines leading away from the interface to represent bulk-mode conversion by the boundary. These components are interconnected by an array of ideal transformers. The precise form of this network is not at present completely known; however, its schematic representation is that of a 'black box' of zero length, in cascade with the lines for the gap and electrode regions, and also with the piezoelectric circuit to be described. In effect, Dirac δ -functions of mechanical force-density are located at the discontinuities.

The piezoelectric network is known, and is simply derived from the Redwood-Lamb circuit[2] by splitting the piezo transformer into two identical parts and removing them to the ends of the transmission line. The effect of this manipulation is most graphically shown by using a two-wire schematic for the line. No sheath is then present, and the only points of attachment are the line ends. The ideal transformers are of zero length and represent piezoelectric δ-functions; they are placed in series with the mechanical transformers so that the gap and the electrode transmission lines have between them two Dirac-sources. Fig. 1 shows the analog network constructed as a cascade of building blocks of the various elements discussed, but with the mechanical circuits omitted. Arrows at the top indicate the piezoelectric forces at the electrode edges, modelled by the piezoelectric transformers of the circuit schematic. Gap and electrode transmission lines are characterized by different acoustic impedance and wavenumber, indicated on the figure.

The circuit schematic as now constituted has a pictorial quality which places in evidence the various physical details of the surface wave structure. In addition to the lines and discontinuity networks described, shunt capacitors, oriented as shown, are required to model the effect of the electric fields that span the gaps and to carry the dielectric displacement current. The ideal piezo transformers on either side of a gap are connected across the same potential differences, but because of the polar nature of the piezoelectric effect, the dot polarities are reversed. Tying the transformer primaries in parallel are interconnections that support the piezoelectric polarization current resulting from the passage of the wave, while the remaining connection, in the electrode region, carries the total electric current. The figure is drawn in keeping with the 'crossed-field' model of the electrical input port, wherein the negative capacitor is absent.[3] Modifications to the network necessary for modelling the 'in-line' circuit follow immediately. Alternatively, the 'in-line' negative capacitor may be modified by Milsom and Redwood's factor [7] if dictated by experiment. A more complete electrical input circuit for excitation by a composite field is described in Reference 12.

A catalog of network components modelling additional structural features such as grooves is still required. Availability of these additional components will extend the gamut of equivalent networks that can be built up virtually by inspection. Even without such a compilation, the analog formulation allows most surface wave devices, such as the recently reported surface acoustic wave crystal resonator[13] to be modelled directly.

The idea that each feature matches up uniquely with its circuit realization provides a sufficiency of parameters to satisfy data, and also highlights the influence of individual physical mechanisms. Additionally, the approximation problem is simplified, since effective line lengths that may be frequency- and material-sensitive do not enter the formulation; all lines are precisely equal to corresponding geometrical lengths. Simplification of the line portions of a network proceeds by making partial-fractions expansions of the arms of the lattice form of the transmission line, realizing these in lumped parameter terms and retaining only those relevant for the frequency range of interest; omitted terms can be tested for significance, and the overall equivalent determined finally in a form consistent with the level of accuracy demanded by application.

CONCLUSIONS

Analog equivalent networks modelling the generation and propagation of acoustic surface waves on piezoelectric crystals lend themselves to in-depth interpretations of the physical processes that occur. Because they are valid continuously along the coordinate of propagation, modification of the circuit picture to accomodate changes in the device structure is extremely simple and straightforward. The modified network retains its physical clarity while remaining in the format compatible with computer-aided circuit design (CAD) programs.

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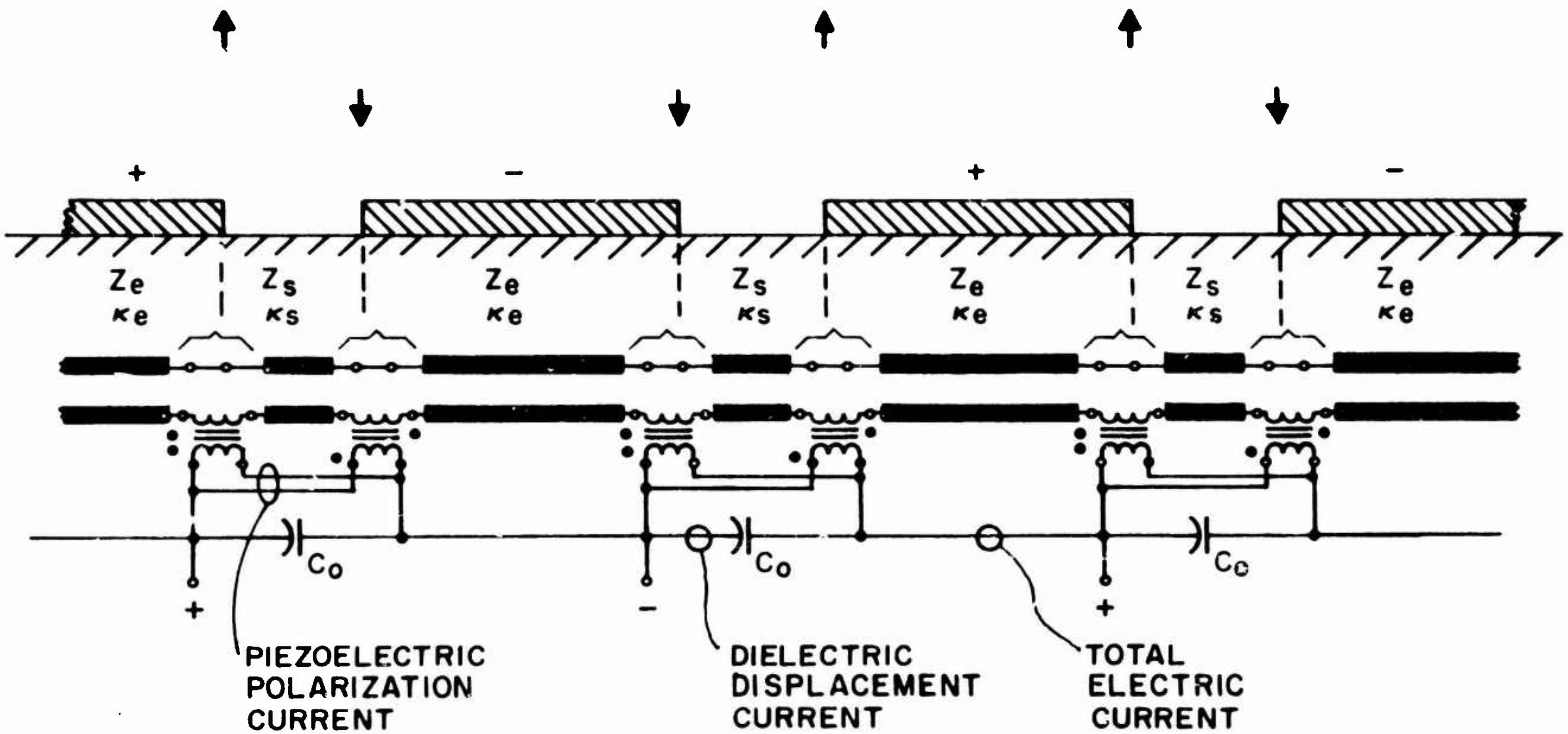

Fig. 1 Analog equivalent network.